Photon Sieve Telescopes

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Photon Sieve

- Essentially a Fresnel Zone Plate with rings broken up into individual holes

- In simplest version holes are same diameter *(d)* as ring width (*w*)

$$r_n^2 = 2nf\lambda + n^2\lambda^2$$

- Can be randomly or regularly distributed with angle

$$w = \frac{\lambda f}{2r_n}$$

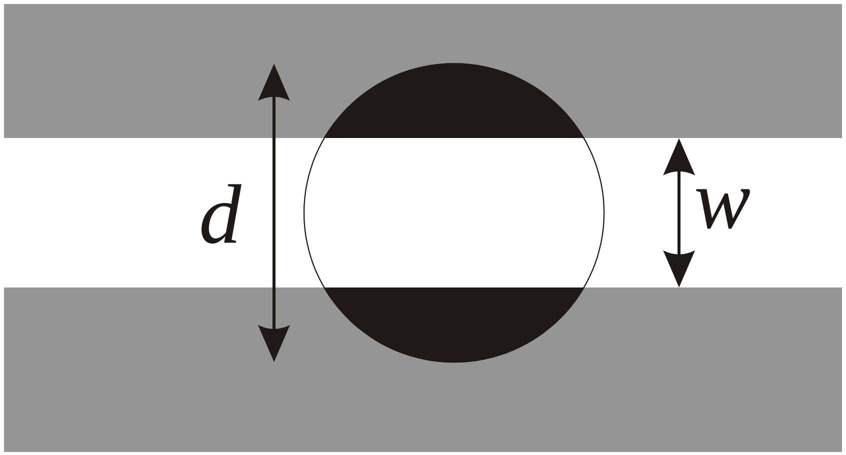
- Can have any density (fill) in each zone as desired

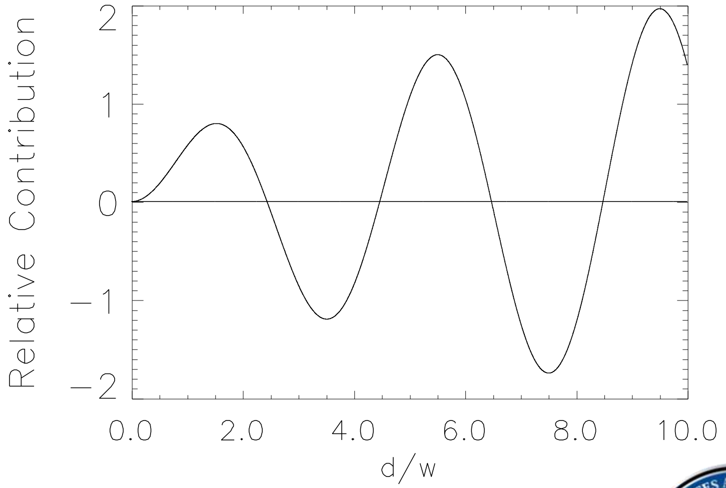
Hole size

- Can make hole size (*d*) > underlying zone (*w*):

$$F \propto \frac{d}{w} J_1\left(\frac{\pi d}{2w}\right)$$

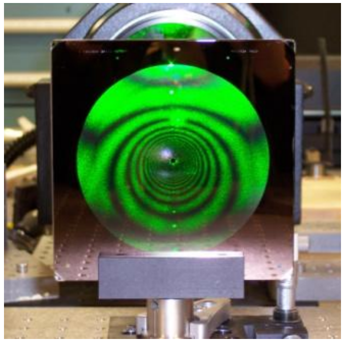
- Still get positive contribution so long as overlap with bright zone is greater than overlap with dark zone

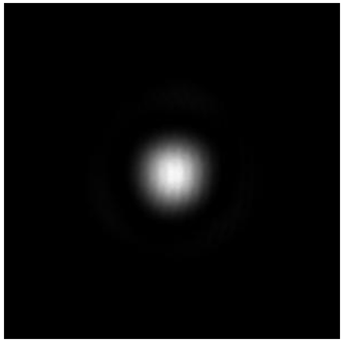


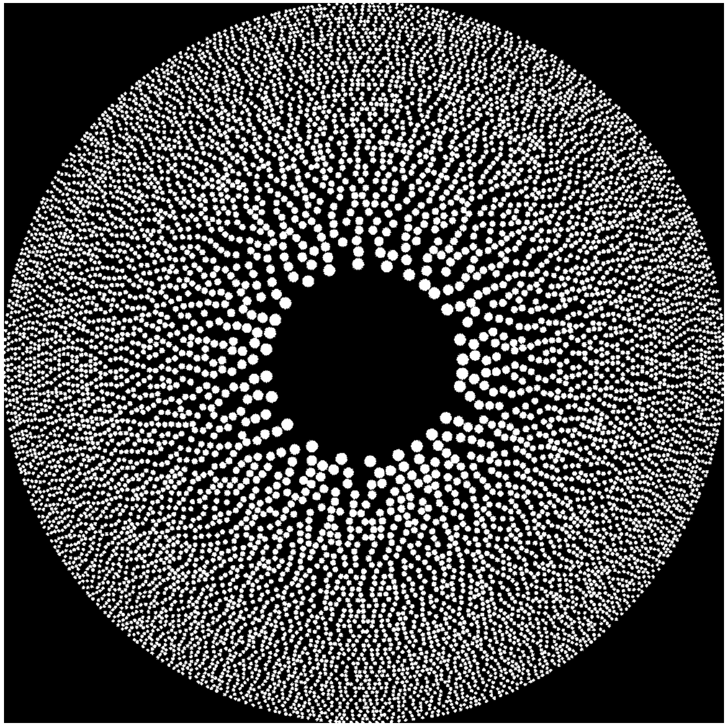


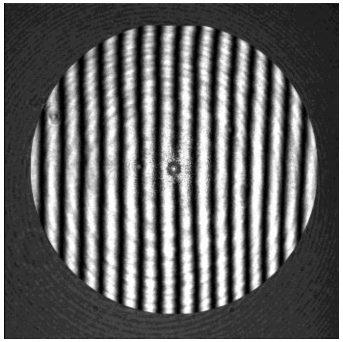
Summary of past work

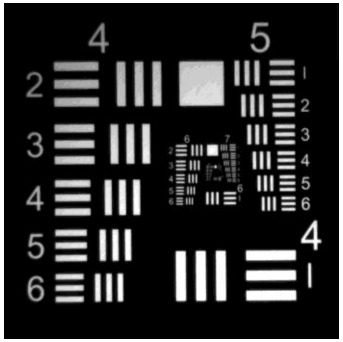
- 4” tests using chrome-coated quartz sieves
  - 5 million holes, 20-330μm in diameter
  - 0.02λ RMS wavefront, 0.98 Strehl







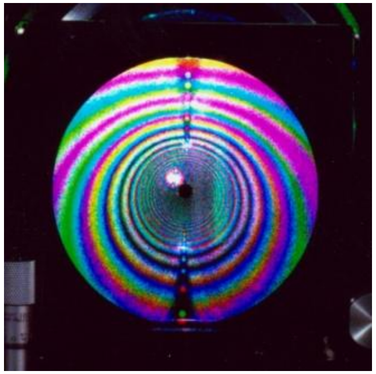




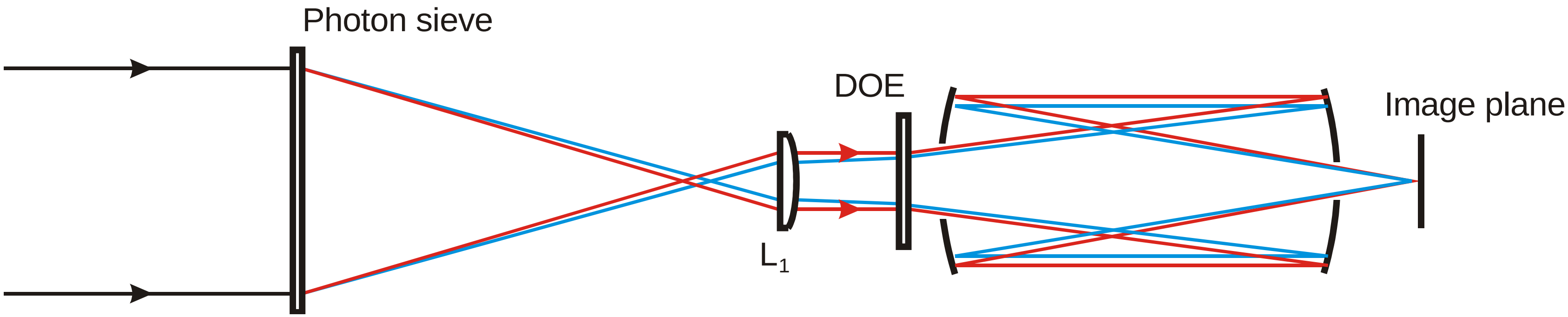
Broadband operation

- Photon sieve is narrowband due to dispersion:

$$\Delta\lambda = \frac{2\lambda f^2}{D^2}$$

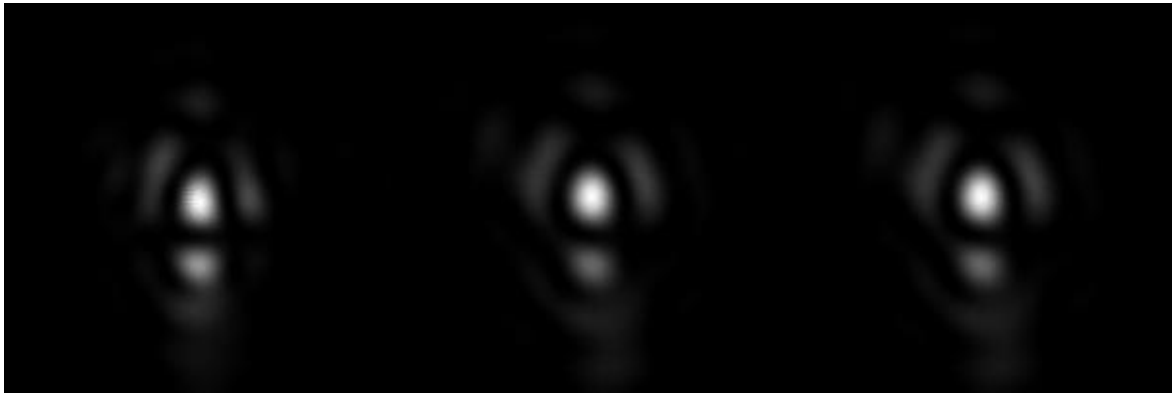


- Correct with secondary DOE (hologram)



Broadband telescope

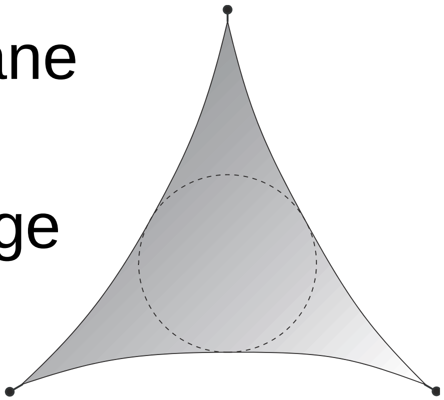
- HOE created in lab: D = 40mm, f = -158mm
- Demonstrated perfect imaging over 40nm bandwidth

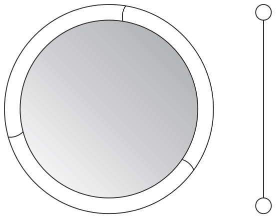


514nm 532nm 543nm

Membrane photon sieves

- Quartz not an option for space applications
- Instead, want to pattern sieve on membrane
- Can be rolled, folded into compact package
- Deployed to larger aperture in space
- Easier to pull flat than form 3D in space
  - Use inflation or tensioning





Thermal Distortion

- In-plane stretching or shrinkage of the substrate will move the holes locations off the zones
- Due to substrate itself or the support structure
  - Not simply a matter of finding a zero CTE polymer
- For a given CTE(α) there will be a shift in the position of the outer ring of Δr :

$$\Delta r = \alpha . r . \Delta T < w/10$$

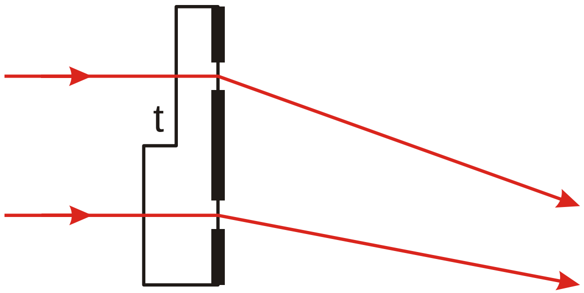
- Typically in the order of $10^{-6}\ °C^{-1}$

Thickness Variation

- Sieve surface may be flat but the phase of the input wavefront is affected by substrate thickness variations
  - Problem for transmissive photon sieves

- OPD between any two zones depends on material thickness, *t* and refractive index, *n*:

$$OPD = t(n-1)$$



- Max thickness error for *n* = 1.45:

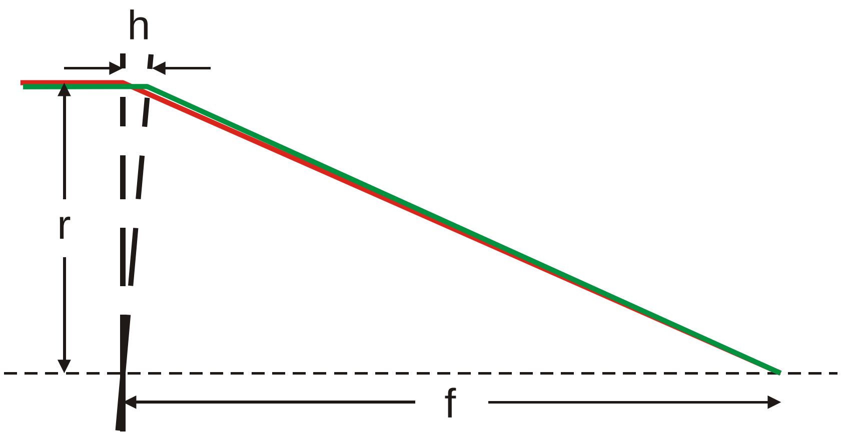
  $\lambda/10$: $t < 0.22\lambda$ (0.11 microns)

Mechanical Deformation

- Surface deformations mean diffracted light is no longer perfectly in phase from one hole to another

- A deviation of height *h* will change the path length of a ray from that point according to:

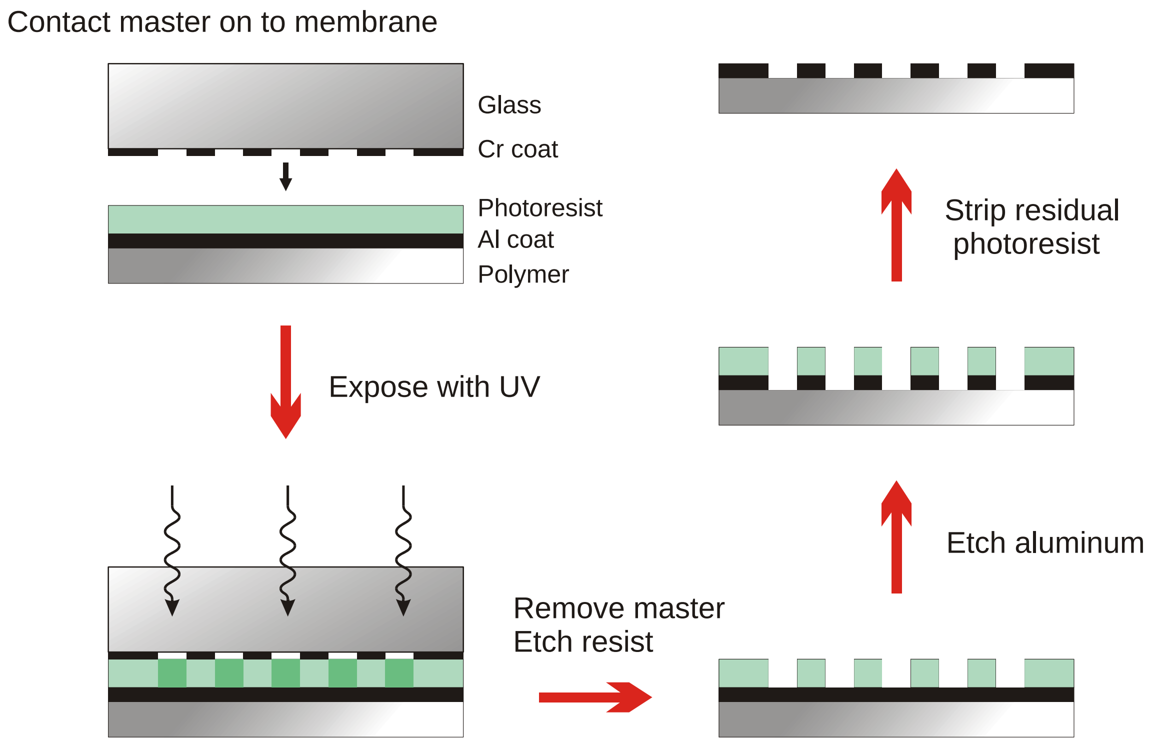
$$h = 2\phi\,(f/r)^2$$



- For D=1m (f/5), $\phi = \lambda/10$:
  - Conventional mirror: $h = \lambda/20$
  - Photon sieve: $h = 20\lambda$

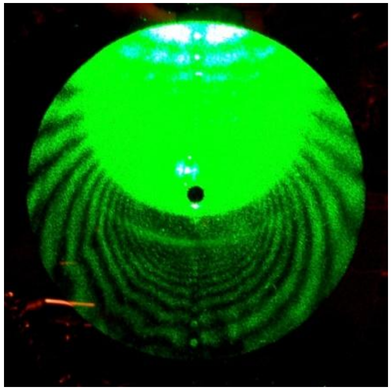
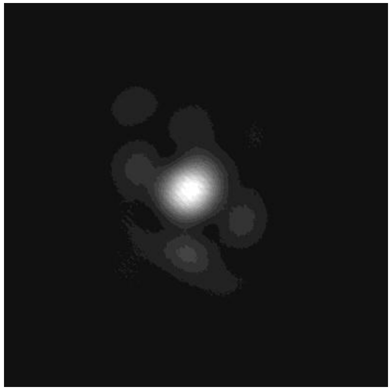
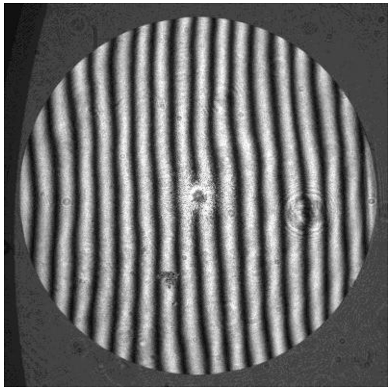
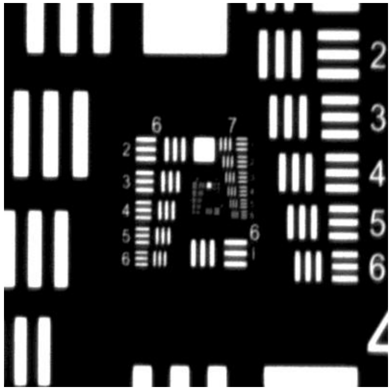
Polyimide film

- 25µm thick polyimide with high thickness uniformity
- Coated with Al and photoresist for contact printing:



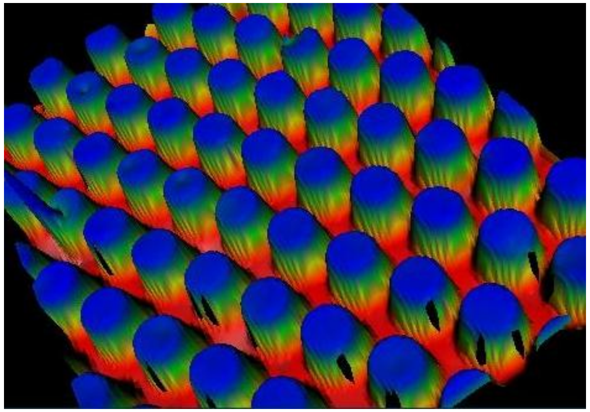
Polyimide film

- Diffraction limited performance
- 0.056λ RMS wavefront error, 0.88 Strehl
  - Even with less than perfect surface flatness evident
- Efficiency of this antihole design was just 0.35%

Intensity vs Phase

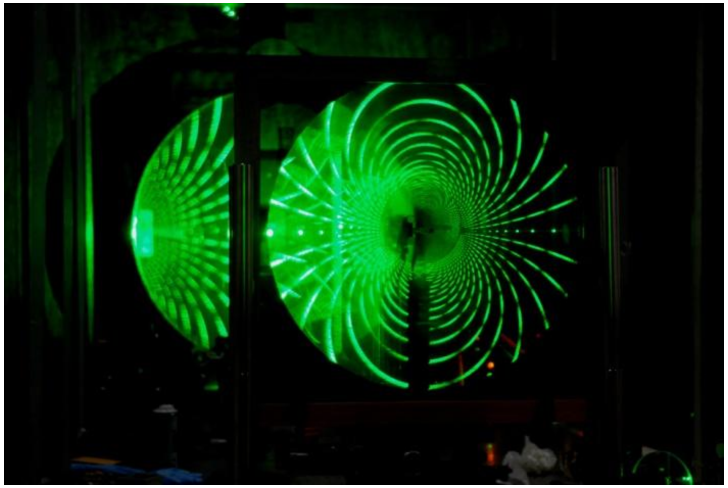
- Transmission photon sieves are binary intensity DOEs with limited diffraction efficiency
- Created photon sieve with optimum 50% fill
  - 3.8 million holes ranging in size from 8-395μm
- Al-coat CP1 films to convert to binary phase DOE
  - Al coating had to be $\lambda/4$ thick
  - 133nm for 532nm light

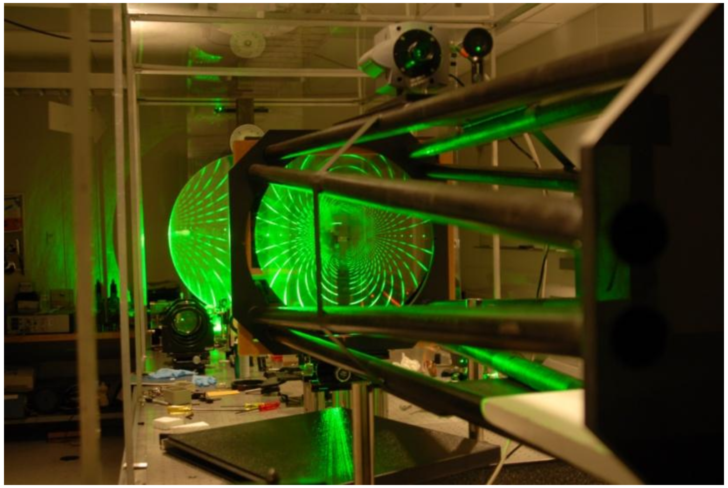


- Efficiency improved from 3.5% to 10%

Other Work

- Have created 0.56m version
  - f=3m, 780 million holes!



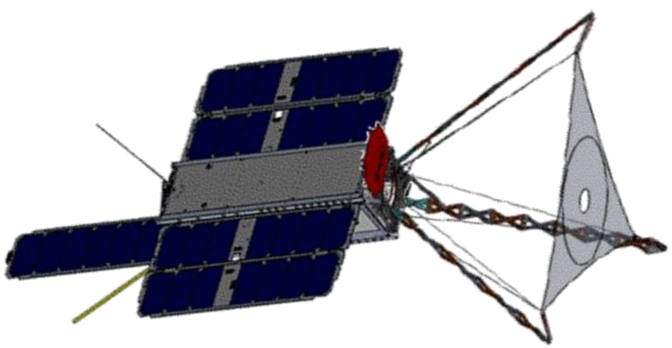


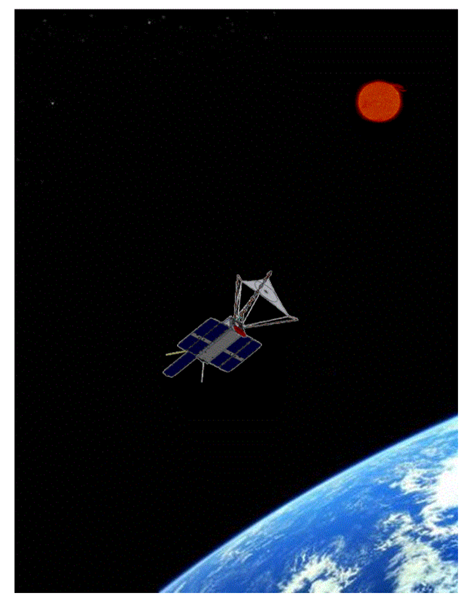
- Formed the basis of MOIRE program:
  - Goal: 20m membrane in GEO (1000kg launch mass)
  - Phase I: Meter-scale demo

FalconSAT-7

- FalconSAT program: cadets design, build, launch and operate small satellite
  - Astro Eng., Physics, Elec Eng., Management, Mech Eng.

- FalconSAT-7: Deploy membrane photon sieve to observe the Sun
  - 3U CubeSat (30cm x 10cm x 10cm)
  - 0.2m membrane photon sieve



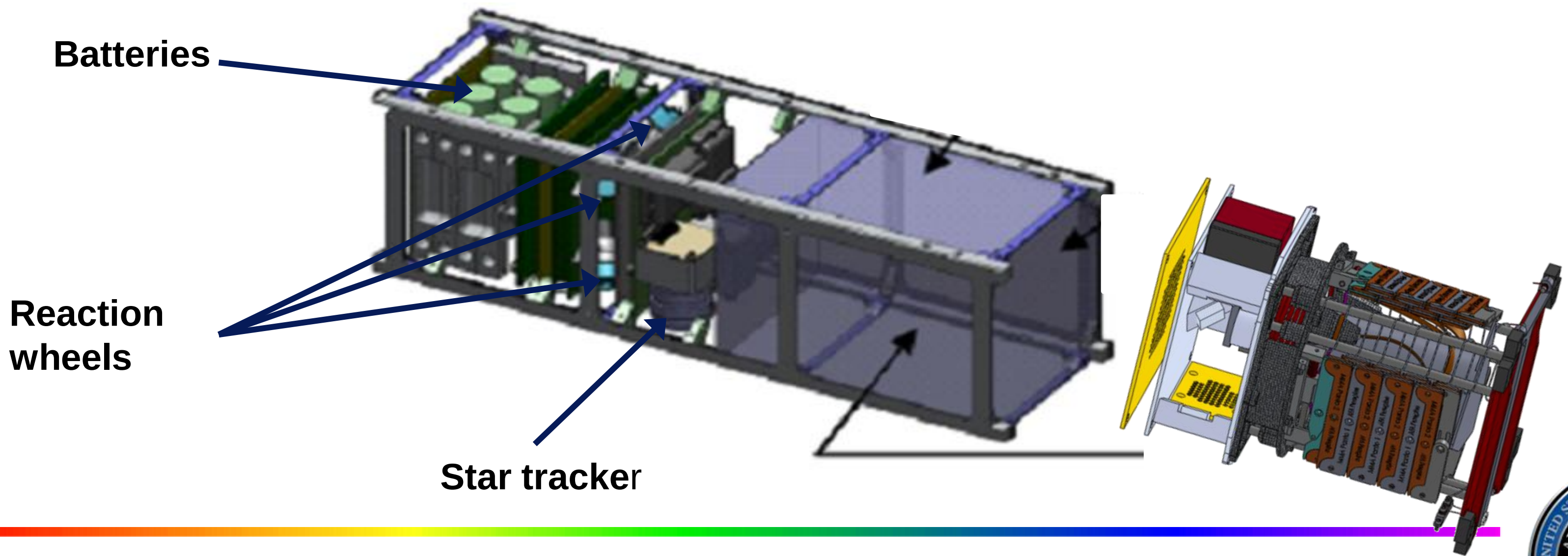


FalconSAT-7 Team

- USAFA – Management, systems integration, science, optics, and electronics
  - NRO – Colony II CubeSAT, launch & networked ground stations
- NASA / Goddard – Science
  - MMA Design LLC – Deployment system design
- AFIT – CubeSAT bus and mission modeling
  - AFRL/RVSV – Membrane analysis

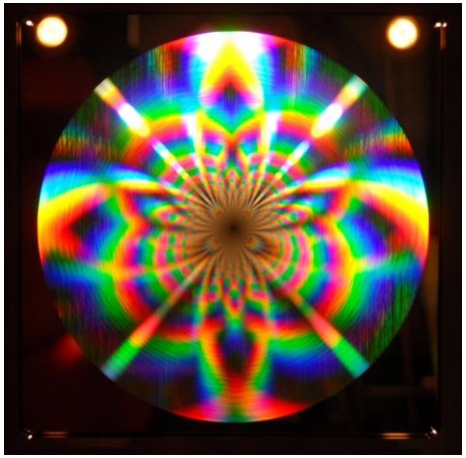
Colony II Spacecraft

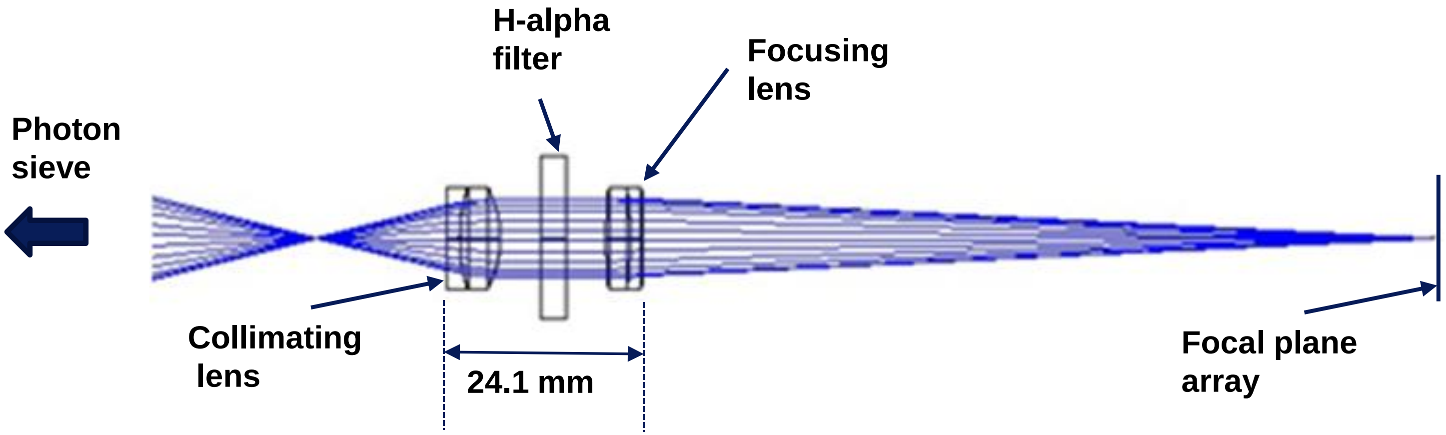
	Capability
Launch Vehicle Interface	Adheres to CubeSat P-POD requirements
Attitude Pointing	0.37° at all times (2σ)
Position Knowledge	±5 km in *x*, *y*, and *z*
Data Rate	50 kbps (between 440-460 MHz and 900-928 MHz)
Payload Orbit Average Power	17.5 W (50% duty cycle)
Peak Power	70 W (for 2 minutes)
Thermal Control	Temperature range is -33°C to +71°C



Photon Sieve

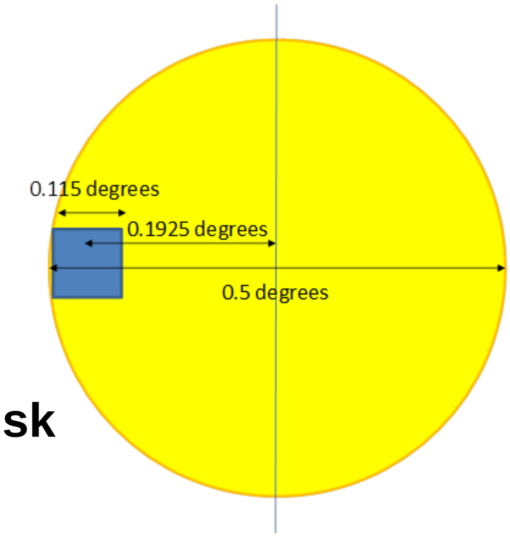
- Binary phase photon sieve
  - Master/contact process or direct-write
- **2.5 billion pinholes (2-277μm diam.)**
- D = 200mm, f = 400mm, λ = 656.3nm
- 50% fill factor, η~30%



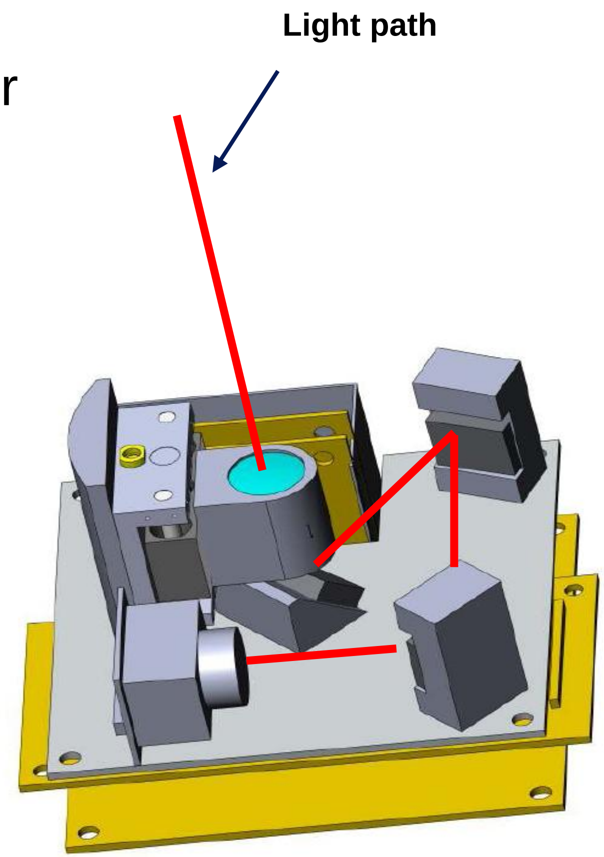


Peregrine Optical System

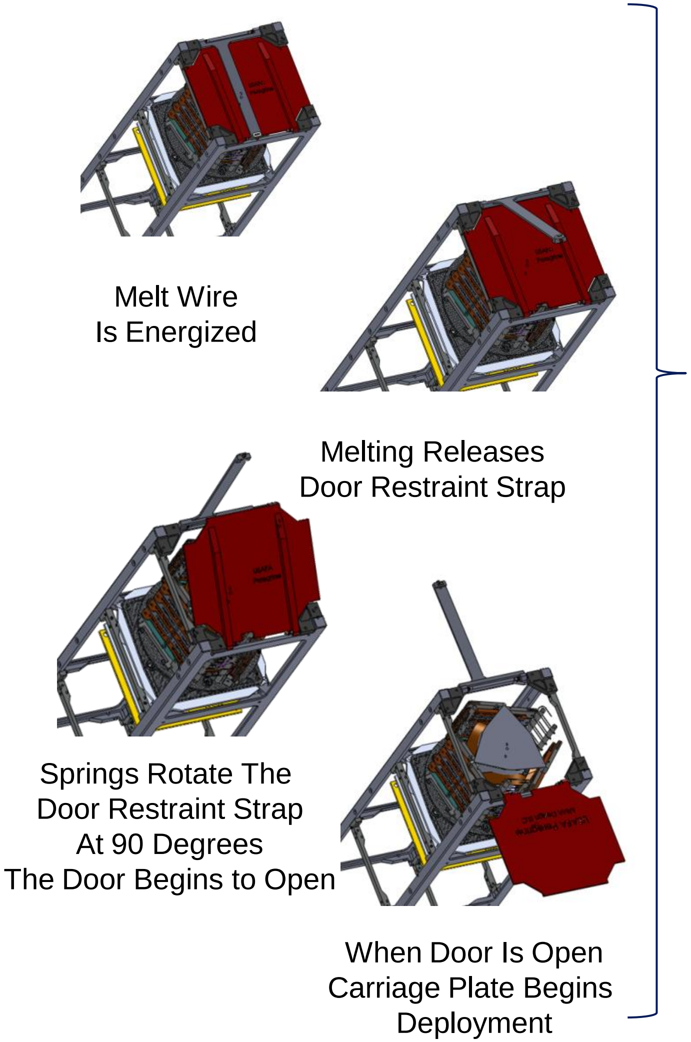
- 2 secondary lenses & H-alpha filter
  - Kinematic adjustment for focus/decenter
- 4 μrad resolution (600 km at Sun)
- ~0.1° FOV, 1Å spectral bandwidth
  - Depends on final choice of camera

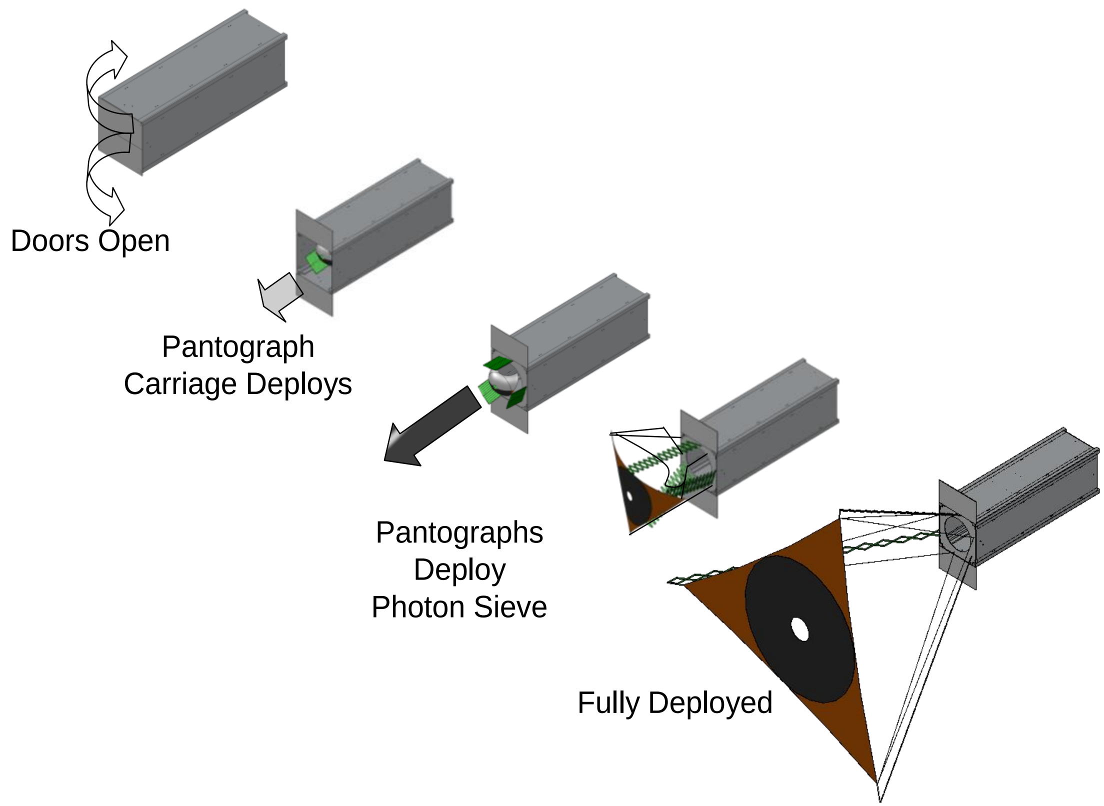


Solar disk



Peregrine Deployment Sequence





Project Schedule

Reviews

- Oct 2010 - System Requirements Review
- Dec 2010 - Conceptual Design Review
- Dec 2011 - Preliminary Design Review
- May 2012 - Critical Design Review

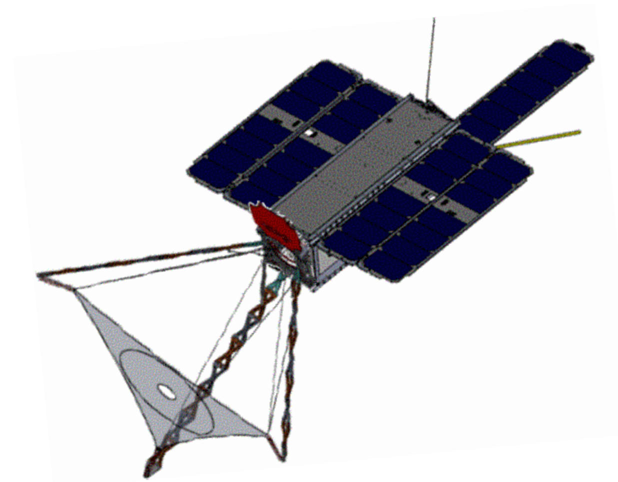
Engineering Model

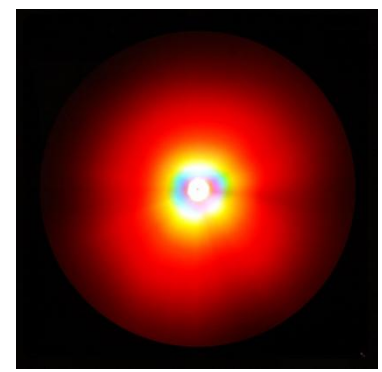
- Aug 2011 - Engineering Bus Arrives
- Jun 2011 - Payload Lab Prototype
- Qual Model
- May 2012 - Payload Qual

Flight Model

- Oct 2011 - Flight Bus Arrives
- Dec 2012 - Payload Flight Model Finished
- Aug 2013 - Payload Integration & Test Complete

Ready for Launch Sep 2013

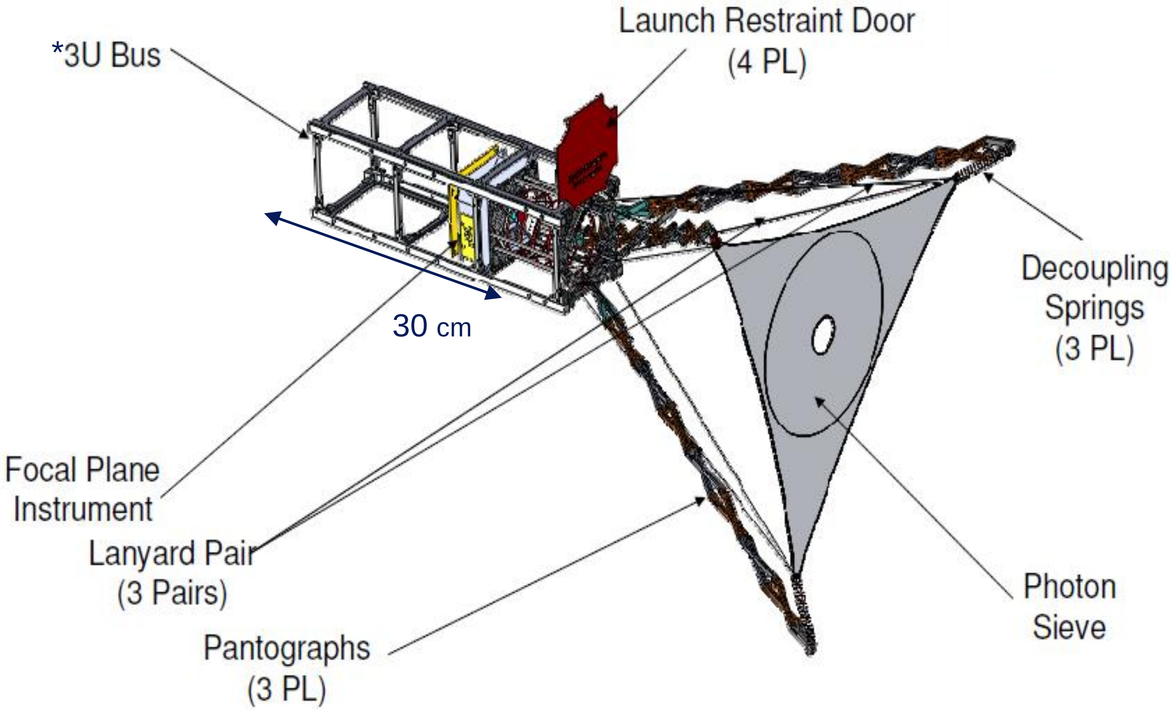




Optical test pattern of photon sieve master

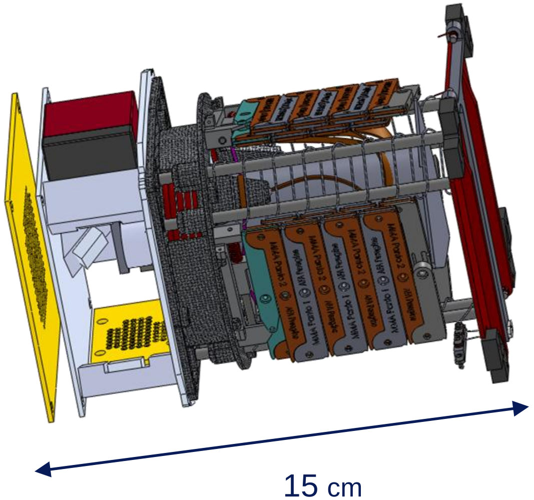
Questions?

FalconSAT-7 System



Jeff Harvey/MMA Design LLC

Peregrine Payload

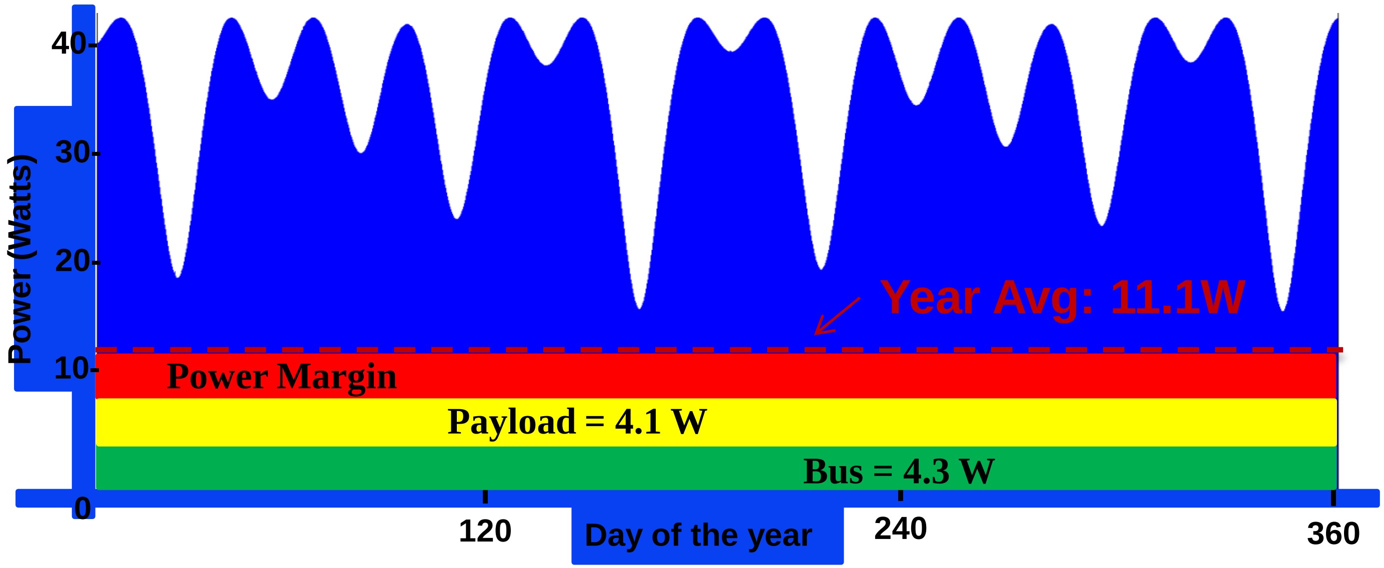


* Avionics not shown

Power

- Power analysis done by AFIT
  - Generated using STK solar panel module (28% eff. cells at 28°C)
  - Sun Beta Angle of 30 degrees

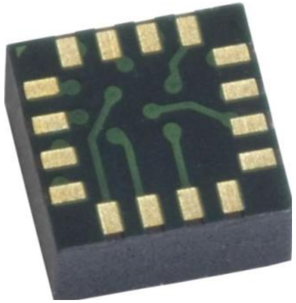
Bus Power Supply
Over 1 Year



- Conclusions
  - AFIT analysis verifies Boeing power estimations
  - Removal of one solar panel will not jeopardize mission
  - Payload requirement: Peak: 6.7 W Average: 4.1 W
  - Power margin: Peak: 63.3 W Average: 2.7 W

ADCS

- AFIT review
  - Assumes baseline Colony-II
  - 700km orbit altitude
- Conclusions
  - Colony II baseline configuration meets FS-7 ADCS requirements
  - Future analysis:
    - Performance at different altitudes
    - Deployed optics effects on ADCS



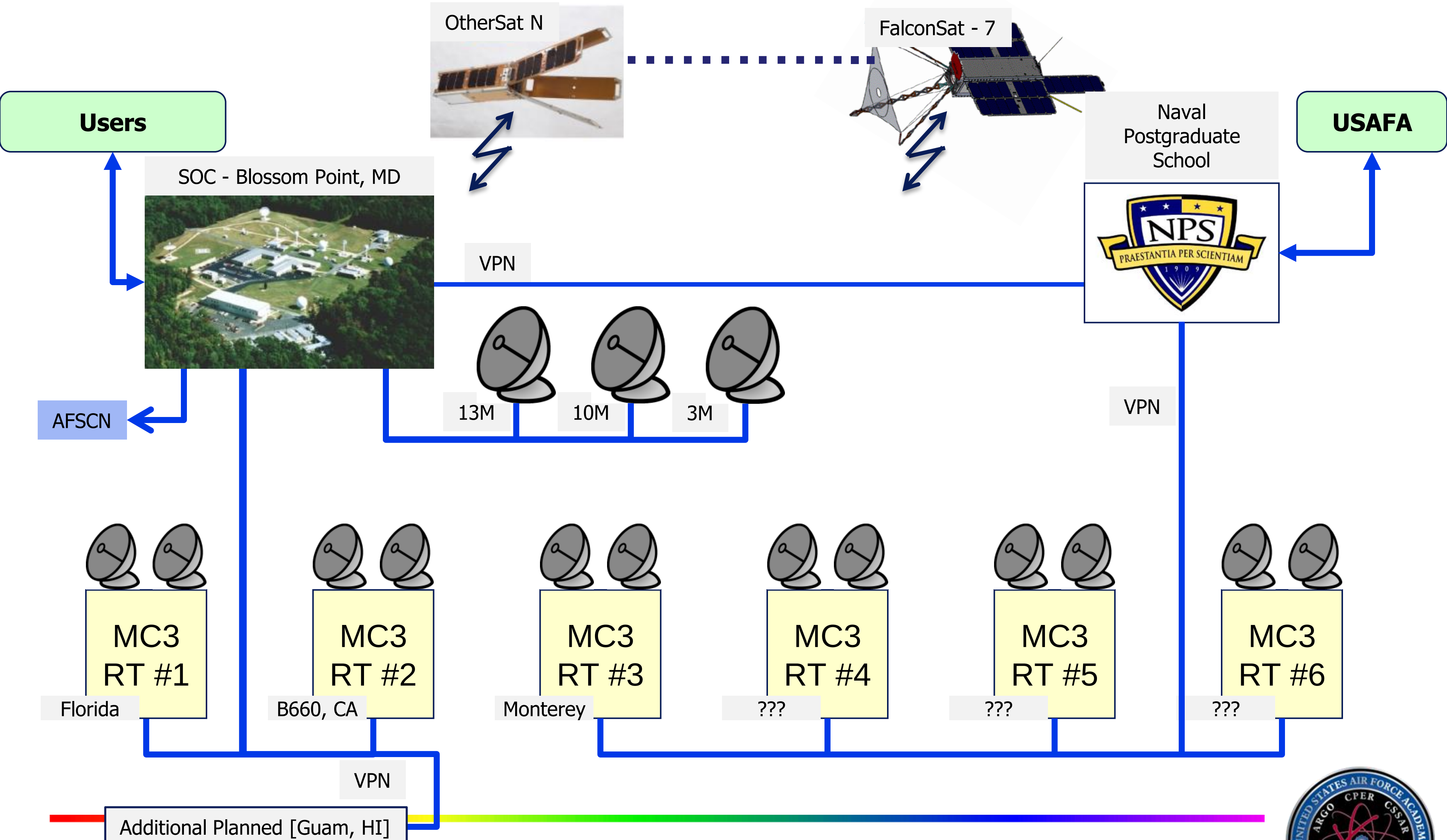
3 Axis Magnetic Sensor by Honeywell

Parameter	Performance Value
Attitude Determination in Attitude Hold	.31 deg (2σ)
Pointing Performance Slew and Hold – 3 axis	.42 deg (2σ)
FS-7 Knowledge Threshold/Objective (Sun Imaging)	±.5/±.32 deg (2σ)
FS-7 Control Threshold/Objective (Sun Imaging)	±.5/±.42 deg (2σ)

Buy CIIB Ground Station

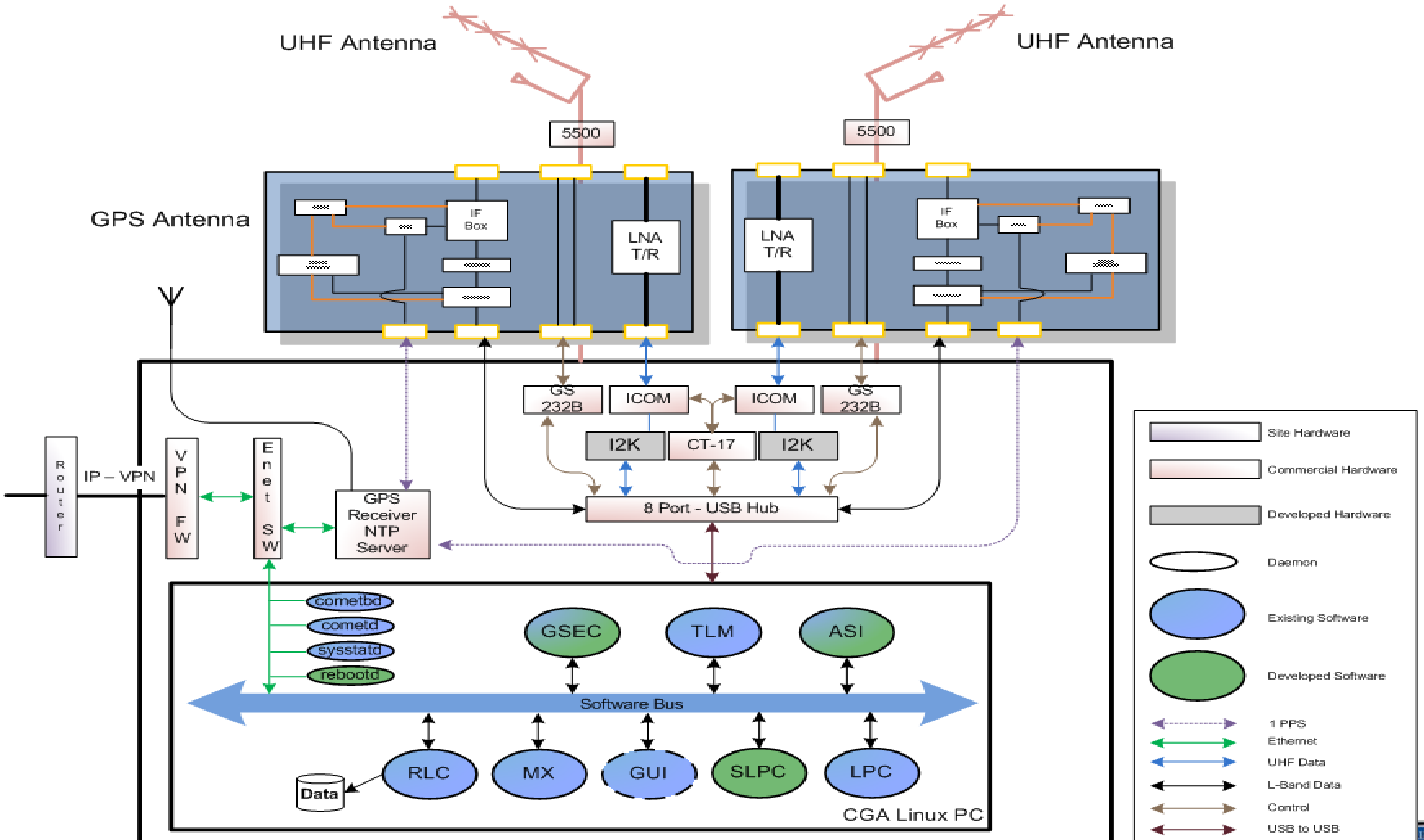
- Prebuilt CIIB GS from NRL.
- Build into current USAFA SatComm architecture
- Advantages: Additional GS at USAFA, singular source of control and decision making over comm. Time with our satellite, access to CIIB network, other ground stations.
- Disadvantages: Cost (80K-100K), already don’t have man hours available, adding to complexity of ground architecture, increasing risk.

CIIB Net



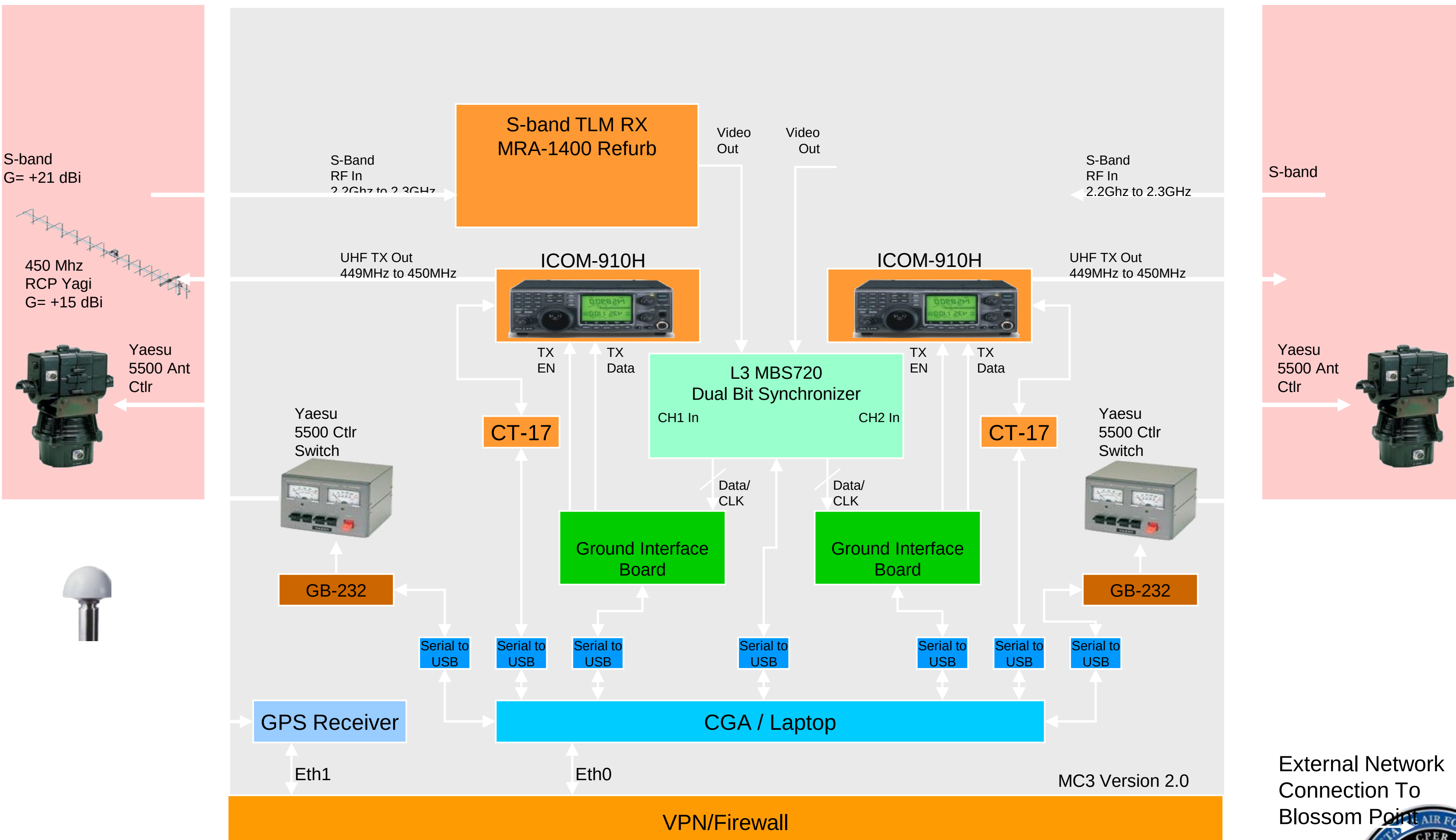
OtherSat N
FalconSat - 7
Users
USAFA
Naval Postgraduate School
NPS
PRAESTANTIA PER SCIENTIAM
1909
SOC - Blossom Point, MD
VPN
AFSCN
13M
10M
3M
VPN
MC3 RT #1
Florida
MC3 RT #2
B660, CA
MC3 RT #3
Monterey
MC3 RT #4
???
MC3 RT #5
???
MC3 RT #6
???
VPN
Additional Planned [Guam, HI]

CIIB Communications System



CIIB GS Architecture

MC3 Version 2.0 Baseline Configuration



Communication

- Colony II Specifications
  - Uplink 450 MHz at 9.6 kbps; Downlink 915 MHz at 57.6 kbps; BER: 1E-5
  - Up to 2 GB storage on bus (shared between payload/bus)
- Payload Requirements

	MBytes/Image		Images/Day		MBytes/Day	
	Threshold	Objective	Threshold	Objective	Threshold	Objective
Sun Imaging	0.346	2	1	10	0.346	20
Earth Imaging	0.346	2	0	1	0	2

  - Payload has additional 2 GB storage (TBR)
  - RS-422 serial connection to bus

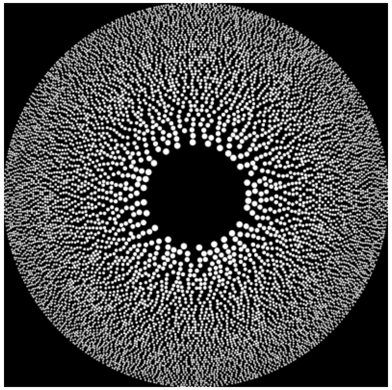
C&DH Module

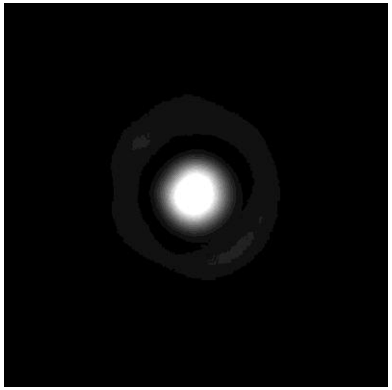
- Communication Analysis
  - Orbit: 450 km i=98°
  - Assume USAFA ground station
  - Sufficient link margin for up/downlink: ~10 dB above required 9.6 dB
  - ~53 sec to download one picture (10% overhead)

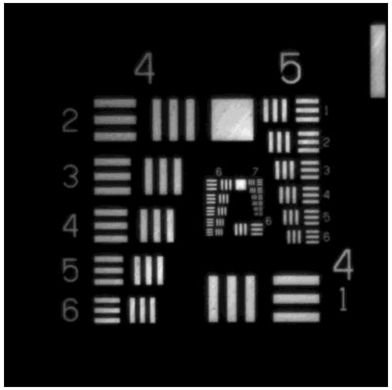
Metal film

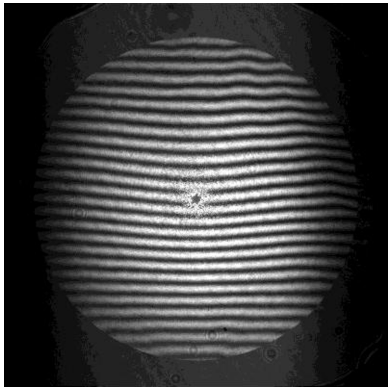
- Made on 12.5μm thick electroformed nickel
  - D= 100mm, f=1m, 5 million antiholes

- Diffraction limited imaging but films too delicate for practical purposes
  - Thicker film not possible with 19μm holes









Diazo film

- Photosensitive polymer for lithography
  - Contact copying of quartz master
- Performance was less than perfect
  - Thick photosensitive layer resulted in blurring of hole images
  - Film had significant thickness variations due to rollers used in fabrication